Solving for Dactyl's Orbit and Ida's Density

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Galileo's recent discovery that Ida has a satellite (now known as Dactyl) suggests that satellites orbiting asteroids may be a commonplace occurrence. In the Solid State Imaging (SS1) data returned from the Ida encounter, Dactyl and Ida appear in 47 images. The locations of lda and Dactyl in these images were used to estimate Dactyl's orbit and Ida's bulk density, which is of great interest to planetary scientists because it may indicate whether or not Ida is composed of rocks that have been thermally processed deep in the interior of a now collisionally destroyed planetesimal. Density calculations were based on an Ida volume of 16,100 km^3 (±1 Z-percent), which was determined from an accurate model of the shape of Ida. While Dactyl's orbit is of interest, the greatest significance of knowing the orbit is that it provides for the first time an accurate estimate of an asteroid's bulk density; another first for Galileo!

Initial attempts to apply classical astronomical orbit-fitting methods to estimate Dactyl's orbit, assuming reasonable values for Ida's density suffered from numerical problems caused by the Galileo-to-Ida line of sight being nearly in the plane of Dactyl's orbit for most of the images. Mike Belton, SS1 Team leader, then asked the Navigation Team to apply their orbit determination methods to the problem. The authors thus became involved in what turned out to be a challenging and enjoyable search for the true orbit of 1)actyl.

Since the objective was to determine *preliminary* estimates for Dactyl's orbit and Ida's density, the analysis was simplified by assuming that Dactyl's orbit was affected only by Ida's gravity acting as a point mass. The problem was to find the orbit for Dactyl that was consistent with the locations of Ida and Dactyl in the SS1 images. Much of the analysis involved reducing the raw data associated with the images (exposure time, camera pointing direction, positions of Ida and Dactyl, etc.) to a form which could be used by a new computer program that would estimate Dactyl's orbit. Another large part of the task involved actually writing and debugging this new program, which was constructed of "QUICK" commands. (QUICK is an easy-to-use, versatile processor from the Section 312 Multimission Analysis Software Library).

It became clear almost immediately that the mass/density of Ida could not be determined at the same time as Dactyl's orbit. To overcome this difficulty, a series of Dactyl orbits were generated for a range of Ida mass/density values from 1.5 to 4.0 gm/cm^3. For each density value, there is a unique orbit; over this range of densities, these orbits differ greatly. For Ida densities less than about 2.1 gm/cm^3, the orbits are just barely hyperbolic. For higher Ida densities, the orbits are elliptical with a large apoapsis (farthest point from Ida), a periapsis (nearest point to Ida) around 80-85 km and periods that range from just over a day to many tens of days. At a density of about 2.8 gm/cm^3, the orbit is nearly circular (about 82 x 98 km), with a period of about 27 hours. For even higher densities, the elliptical orbits have apoapses of about 95-100 km, with periapses which decrease with increasing density. For an Ida density greater than about 2.9 gm/cm^3, the periapse is less than about 75 km and the period is less than 24 hours. The geometry for a range of orbit solutions is shown in the accompanying figure. Since this view is from the spin pole of Ida, the motion of Dactyl and Ida's rotation are both counterclockwise.

The figure shows that when points at the same time on each Dactyl orbit arc connected, they fall along straight lines parallel to the center line through Ida that points to the spacecraft. All of the images but the very last were taken when Galileo was thousands--or even hundreds of thousands- -of kilometers from Ida and nearly in its equatorial plane, so that Galileo was viewing the Ida/Dactyl system from the lower right part of the figure. For scale, the long axis of Ida is 58 km, and the Ida orientation shown is at the time of Galileo's closest approach. Thus, the area of the figure covers only a few hundred kilometers around Ida.

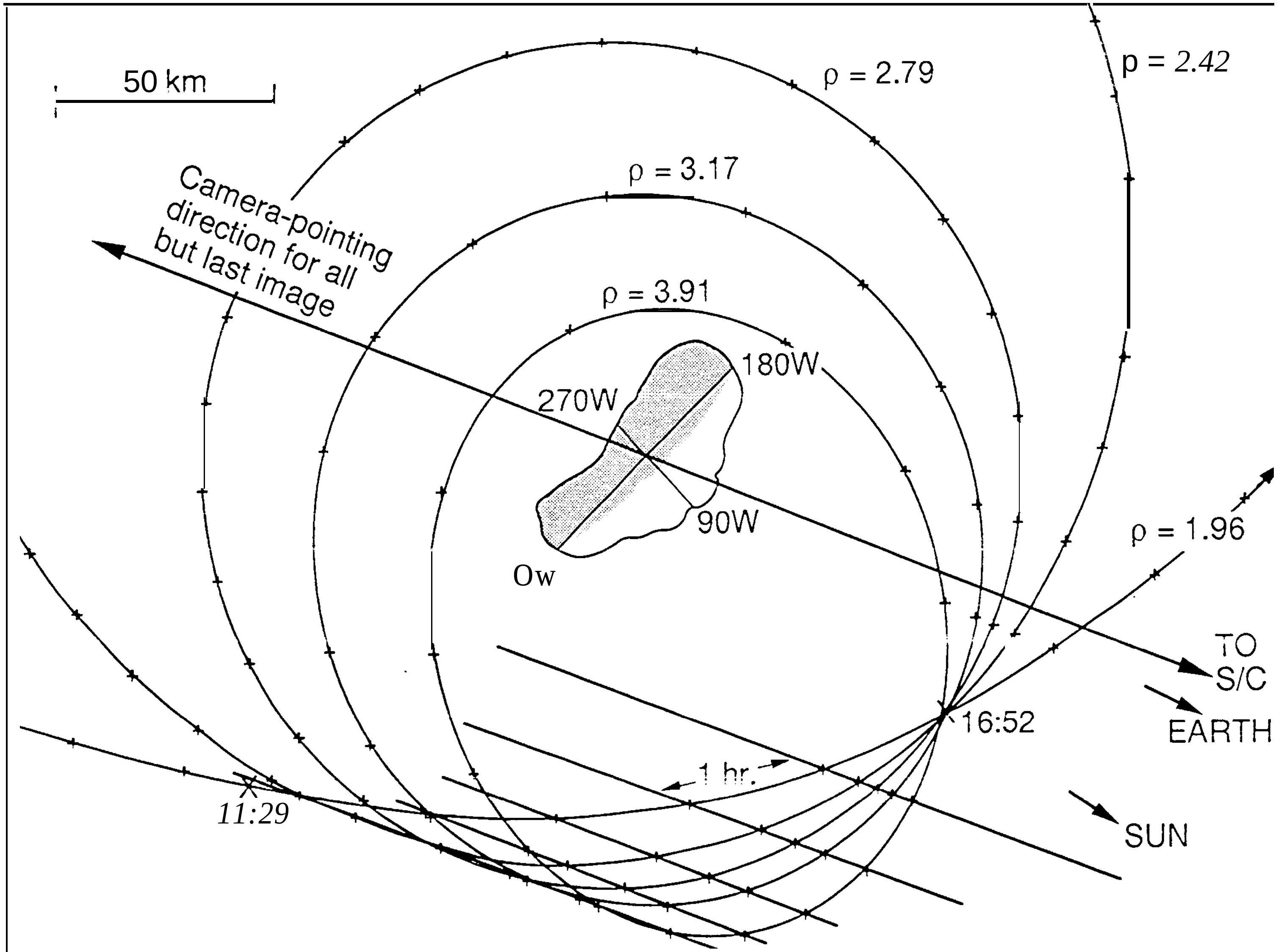
The last image mosaic was taken when Galileo was almost at its closest approach to Ida and included parts of both Ida and Dactyl in separate images. At that point, Galileo was essentially looking down on Dactyl's orbit plane (essentially the plane of the figure), and Dactyl was at the point where all of the possible orbits cross. The lowest of the parallel lines connects the points on each orbit at 5 hours prior to closest approach, or about the time of the earliest image. Since Dactyl was viewed for only a fraction of its orbit and from a nearly edge-on vantage point, all of the orbits shown fit the observations equally well. If one imagines being on the Galileo spacecraft looking at Ida and Dactyl, then all of the orbits would have appeared the same during the 5-hour approach, since the differences between them are all along the line of sight (the parallel lines in the figure.)

Thus, for a given mass/density of Ida, a unique and well determined orbit can be found. However, this alone does not help in finding tile unknown density of Ida. Only by applying the dynamics of motion about a non-point-mass Ida and knowledge of the genera] distribution of material in the entire asteroid belt can the range of possible mass/density values for Ida be reduced.

Dynamical studies show that orbits which have periapses less than about 75 km from Ida arc unstable and either collide with, or escape from, Ida—-thus, orbit solutions arc not physically possible that correspond] to an Ida density of about 2.9 gm/cm^3 or greater. At the other extreme, hyperbolic and even highly elliptical orbits around Ida are very unlikely. The observed speed of Dactyl around Ida for *any* of the orbit solutions is no more than about 10 m/s, about the speed of a fast run or a slowly thrown baseball. Calculations indicate that the chance of an asteroid the size of Dactyl passing by Ida at that speed, just when Galileo was observing it, are about 1 in 10^{19}. In addition, if Dactyl were in a hyperbolic or highly elliptical orbit, it should have been seen by the Hubble Space Telescope (HST) when HST observed the region around Ida over a period of 8 hours on 26 April 1994. HST would have easily seen Dactyl had it been more. than about 700 km from Ida. Combining these two restrictions gives a preliminary estimate for Ida's bulk density of 2.1 to 2.9 gm/cm^3. Allowing for a 12-percent uncertainty in the modeled volume of Ida increases the range to 1.9 to 3.2 gm/cm^3.

This density range is surprisingly well constrained and the low value suggests that Ida is fairly porous and/or made of" fairly light rocks. 'his result already excludes several classes of dense igneous rocks that had previously been suggested as the primary components of Ida's composition.

Further work on the long-term stability of orbits that fit these observations, as well as a more precise analysis of the SS1 images themselves, will lead to future improvements in the determination of both the density of Ida and the orbit of Dactyl. This improved knowledge, combined with other ongoing work involving the color, spectral properties and geology of Ida's surface, is expected to lead to major advances in our knowledge of the nature of the asteroids and what they can tell us of the birth of the planets.



Notes:

- Ida rotates in *4.63* hours
- p = Density

- Ida is shown oriented as it was at 16:52:05 (UTC) on Aug. 28, 1993

Dactyl Orbit Parameters vs. GM
47 Pictures
(Ida Equatorial Coordinate System*)

GM	Density#	a **	e	i	Ω	ω	f	w + f	P	Rp	Ra	WRMS
(km^3/s^2)	(gm/cm^3)	(km)		(deg)	(deg)	(deg)	(deg)	(deg)	(hrs)	(km)	(km)	(pixels)
0.00180	1.68	39.5	2.75	170.13	-23.14	-30.27	41.97	11.71		69.2		0.206
.0.00190	1.77	53.9	2.31	170.23	-23.43	-29.30	40.73	11.43		70.8		0.178
0.00200	1.86	80.1	1.91	170.34	-23.73	-28.11	39.23	11.12		72.6		0.165
0.00210	1.96	136.3	1.55	170.48	-24.03	-26.70	37.51	10.81		74.5		0.162
0.00220	2.05	319.0	1.24	170.62	-24.30	-25.08	35.61	10.52		76.4		0.165
0.00225	2.10	710.2	1.11	170.69	-24.42	-24.22	34.62	10.40		77.3		0.168
0.00230	2.14	4100.0	0.98	170.77	-24.55	-23.20	33.46	10.26	9554.0	78.2	8122.0	0.171
0.00235	2.19	619.8	0.87	170.84	-24.65	-22.20	32.35	10.15	555.6	79.1	1160.6	0.174
0.00240	2.24	343.9	0.77	170.92	-24.75	-21.01	31.04	10.04	227.3	79.9	608.0	0.177
0.00250	2.33	197.9	0.59	171.07	-24.93	-18.26	28.10	9.84	97.2	81.5	314.2	0.183
0.00260	2.42	147.6	0.44	171.21	-25.09	-14.60	24.27	9.67	61.4	83.0	212.2	0.187
0.00280	2.61	107.2	0.21	171.48	-25.34	0.05	9.35	9.40	36.6	85.1	129.4	0.194
0.00290	2.70	97.3	0.13	171.62	-25.45	19.52	-10.24	9.28	31.1	85.1	109.5	0.196
0.00300	2.79	90.3	0.09	171.75	-25.54	62.67	-53.48	9.19	27.4	82.5	98.1	0.197
0.00310	2.89	85.2	0.11	171.88	-25.62	105.80	-96.70	9.10	24.7	75.8	94.6	0.198
0.00320	2.98	81.3	0.16	172.00	-25.69	125.23	-116.20	9.02	22.6	68.3	94.4	0.198
0.00340	3.17	75.9	0.26	172.25	-25.82	139.60	-130.71	8.90	19.8	56.0	95.8	0.198
0.00360	3.35	72.4	0.35	172.49	-25.92	145.51	-136.71	8.80	17.9	47.0	97.8	0.196
0.00380	3.54	70.0	0.42	172.74	-25.99	148.95	-140.22	8.73	16.6	40.3	99.8	0.195
0.00420	3.91	67.4	0.54	173.21	-26.08	153.19	-144.55	8.64	14.9	31.0	103.7	0.190

Epoch = 8/28/93 16:52:04.7 UTC

"*Ida* pole *(IAU convention): RA=338.0 deg, DEC=87. O deg in EME2000*

● *Positive for hyperbola

#Assumes *Ida volume* = 16,100 *km*^3

WRMS = weighted root mean square of residuals

LAD 12/19/94